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Fixed 5th Generation Advanced and Beyond

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Executive Summary

One of the overarching goals of the ETSI Industry Specification Group (ISG) F5G on Fifth Generation Fixed Network is to establish a regular rhythm of evolution for the fixed telecommunications network. This technology enhancement corresponds to the series of generations defined for the wireless network. So far, F5G has published technical specifications on use cases, generations definition of fibre networks, architecture, and more. As it continues, these documents will be enhanced and revised to describe the fifth generation of fixed networks more fully. Therefore, we need to consider the evolution of F5G. This White Paper describes the drivers, dimensions, and technologies of the F5G advanced and beyond.

Nine key applications or industry trends are identified as key drivers for F5G Advanced. These can be grouped into two categories: those that are oriented towards services and applications, and those that are directed towards network transformation. Ultra-high-definition immersive experience services could put many new requirements on the network. Enterprises will continue their digitization and cloudification, and this is a huge opportunity for fixed networks. Industrial applications of fibre networks offer completely new markets for providers as well as add value for manufacturers. The metaverse could be a driver for new infrastructure capabilities. The digitization of network operations can help to reduce operational costs and improve service agility. Optical fibre infrastructure continuing to expand, becoming nearly ubiquitous. Smart society infrastructures can improve services for all while reducing their cost. Overcoming the green challenge is critically important for the planet and the sustainability of the network. At the same time, the business environment continues to change, and this can have major impacts on the network.

Given all of these drivers, the capability of the network is envisioned to increase in six main dimensions. Networks will become faster, increasing bandwidth to accommodate more services. They will become quicker, reducing latency as much as physically possible to enable new applications. Networks will also become "wider" by increasing the network scope and number of endpoints, and greener by enhancing energy efficiency in several ways. Information systems will become smarter by integrating computing power into the network at all levels. Networks will also become more aware to help improve operations and maintenance. Given the pervasive nature of the fixed network, trustworthiness of networks is also very important.

To propel the growth of the network along these six dimensions, various new technologies will be needed. Network technologies including 800G+ OTN and related systems, Sub-1G OSU-OTN, Optical cross connects, 50G-PON, novel PON functional splits and capabilities, and Wi-Fi 6e and 7 will all be required. Fibre technologies will be advanced to support FTTRoom (FTTR), FTTMachine, and FTTCampus/Office. Latency will be controlled using techniques such as deterministic networking, end-to-end slicing, and edge computing. Energy efficiency can be supported at the network, equipment, and application levels. Technologies for high quality computing networks and distributed Computing include optical computing, network information gathering, elastic resource scaling, latency-aware process dispatching, joint optimization of optical network and cloud computing resources. To enable autonomous network management, techniques such as intent-based management, knowledge graph for fault management, and network information gathering can be used. Network-based sensing systems include fibre cable digitization, distributed optical fibre sensing, and Wi-Fi sensing.

Figure 1 illustrates the relationship and rhythm of fixed network generation evolution.

Figure 1: Illustration of the F5G advanced roadmap

1 Key Driving Forces for F5G Evolution

There are many drivers that motivate the advancement of F5G networks towards their next evolutionary step. These can be grouped into two categories. The first are those that involve the digitization or cloudification of various service or application domains. The second are those that involve improvements in the network infrastructure itself for various purposes.

1.1 Digitization or cloudification of applications

1.1.1 UHD immersive experience services

In many broadband service scenarios, real-time resource visualization, Wi-Fi adaptive optimization, and dynamic assurance of user-level service experience will be needed to meet requirements for premium home broadband. While there are many possible services, the most important promises to be ultra-high - definition (UHD) immersive experience services due to its wide impact on both the network and the user. On the network side, such immersive services will likely be the largest single user of bandwidth, and that bandwidth is to be provided with low latency to be effective. The impact on user behavior could be significant. One example would be that immersive on-line meeting services could lead to reduced need to travel and hence reduced travel related carbon emissions.

In home scenarios, FTTR and Wi-Fi provide gigabit coverage for the entire house, networking smart home appliances with a 10-fold increase in the number of connections.

1.1.2 Enterprise digitization and cloudification

Premium computing integrated networks enable operators to offer new capabilities and resources in an “X as a service” model. Since the economic benefit of cloudification is more and more understood, several approaches are being taken by enterprises ICT actors. That means more flexible ways of offering communication, storage, and computing as a service are needed to meet a particular enterprise’s requirements.

Using a more “as a Service” model, more intelligence for service creation and customer interaction is needed. The flexibility and adaptability to customer needs should be reflected in the customer facing systems. For hybrid cloud-oriented approaches, smarter ways to connect enterprises with cloud hosted resources enable customers to choose the services needed for their business operations.

For operators' high-value premium private line services various improvement can be foreseen. These include multi-parameter path computation, short service provisioning, Customer Premise Network (CPN) management as a service, self-help, and self-install. The goal is to help operators increase revenue (extension of business) and improve efficiency (autonomic management).

Enterprise digitization and cloudification may lead to energy aware optimization of the balance between computing, storage, and transport in edge cloud architectures with the aim of reducing the total energy consumption. Enterprise cloudification and digital transformation, large-scale network construction by FMC operators, and rapid development of 8K/VR/XR video services can have significant impact on the energy consumption of the network. All of these require green all-optical networks with 10-fold energy efficiency improvement.

In campus scenarios, there are still 100 million SME locations worldwide that require fibre connections. Therefore, a FTTO solution that features simplified ultra-broadband and multi-service guaranteed bandwidth isolation is required for extensive coverage.

1.1.3 Industry going fibre

The digitization of Industry 4.0 will bring the introduction of more machine vision, industrial sensors, and remote interactive applications. Industrial optical networks provide unique large bandwidth, high reliability, and high immunity to electromagnetic interference (EMI). They are becoming the mainstream solution of industrial production network construction and have the potential for up to 10 billion Fibre to the Machine (FTTM) connections.

Digitization in industries requires high speed, high real-time performance, and reliability of networks. While the specific application will determine the exact requirements, the following gives an approximate idea of the level of performance required. The Customer Premises Network (CPN) can be divided into the production line and campus segments. The production line field bus may need 1 us level latency, 20 ns level jitter, zero packet loss, and 99.9999% reliability. The industry campus network may need 100 us level latency, 1 us level jitter, zero packet loss, and 99.999% reliability. The industrial WAN network interconnects the campus to the headquarters or cloud. It may require 1 ms level latency, microsecond level jitter, zero packet loss and 99.999% reliability. It will also need to support multiple services with the isolation capability.

1.1.4 Metaverse as a Driver for new infrastructure capabilities

The concept of metaverse first appeared in the Avalanche, written by American science fiction writer Neil Stevenson in 1992. It describes a cyber world parallel to the real world, the metaverse, where people in the real world all have a digital avatar; they interact and live with each other through these avatars. Today, the metaverse encompasses many diverse elements such as F5G-Advanced, AI, cloud, and content creation The core idea of metaverse is to continually optimize users' digital life experiences through XR (extended reality) and continuous iteration of XR technology and equipment. XR-based digital services will gradually penetrate various scenarios and drive breakthroughs in the disruptive immersive digital life experience of the metaverse. If this grows to a critical mass, then the era of the metaverse may begin.

The infrastructure for such metaverse applications consists of access network, transmission network, content pre-processing, edge computing, and the cloud. The F5G-Advanced network is this infrastructure.

1.2 Network infrastructure improvements

1.2.1 Digitization of network operations

Simplification of network operation is needed since networks and their integration with computing power will increase the number of elements controlled and managed. Therefore, simplification of Operation Administration and Maintenance (OAM) through autonomous driving network approaches are essential for the ease of operation and reduction of operational costs.

With the rapid growth of the network scale, the number of users, devices, and service types will increase. Network and service OAM urgently needs to become more digitized and intelligent. Core technologies, such as service intent, multi-dimensional experience awareness, and adaptive network adjustment, can be used to upgrade the network management system to a higher autonomous network level (ANL), as defined by Telecommunication Management Forum (TMF). It includes achieving close to zero wait for services, zero touch for network maintenance, and zero trouble in services.

The carbon emissions that occur due to the operation of the networks should not be neglected. A major item of cost and emissions is the field operations needed to fix network faults and perform maintenance. Self-operating networks could lead to a significant operational expense reduction and reduce the amount of people and equipment needed to maintain and repair the network. It would reduce the number of trips to fix failures. The ultimate goal is a self-healing network.

1.2.2 Optical fibre infrastructure becoming ubiquitous

Optical networks are becoming ubiquitous. This leads to networks fit to offer enhanced services, to better offload of mobile and/or wireless networks (e.g., Wi-Fi), and to be more energy efficient.

Optical fibres have obvious advantages over copper lines in terms of cost, safety and reliability, electromagnetic interference immunity, and long-distance expansion capability.

With the rapid development of fixed network services in just ten years, the investment for constructing optical fibre infrastructure networks is considerable. Carriers' investment in optical cable networks is more than half of the total investment in fixed networks. However, as a passive infrastructure asset, fibres also face management difficulties such as passive resource accumulation, fictitious occupation, and invisibility. The Operation and Management (O&M) pain points include difficulties in fault demarcation and locating. New technologies and architectures need to be introduced to build a digital optical fibre infrastructure profile. This facilitates the visualization of fibre core-level passive resources, topologies, and connection status of the Optical Distribution Network (ODN). This can improve the overall O&M efficiency of optical fibre infrastructure and the automation capability of upper-layer service networks.

At the same time, optical fibres can also be used as "sensors" to capture and collect environmental information such as vibration, stress, and temperature changes. The optical fibre sensing technology represented by DAS (Distributed Acoustic Sensing) has been applied in oil and gas pipeline intrusion monitoring and coal mine conveyor belt monitoring. It has been used for perimeter security, realizing unmanned patrol inspection. These have effectively reduced the risk of oil and gas pipeline accidents and greatly improved the operational efficiency of the energy industry.

1.2.3 Smart Infrastructures for a Sustainable Society

As the Smart Society develops, computing power integrated networks become the new foundational infrastructure for all areas of digital life. Those new infrastructures need to adapt to the special needs of the various stakeholders in the society. The digital transformation is calling for this type of infrastructure for almost all areas. Since the infrastructure is foundational and should be able to meet a plethora of requirements, the flexibility, adaptability, and trustworthiness are major features of those infrastructures.

One aspect of the digital transformation is the move towards more artificial intelligence-oriented services and applications. Additionally, the needs for flexibility, adaptability, and efficiency in infrastructure operations requires artificial intelligence (AI). From a business perspective, users might want to consume artificial intelligence services from the infrastructure in an “AI as a Service” model offered as part of the smart infrastructure.

The integration of computing, storage, and communication requires orchestration of the various resources and infrastructure components. It needs to take the next step towards autonomous infrastructure operation and requires a certain degree of intelligence. Specifically, the dynamic scaling of each component and resource functionality needs to react to changes in demand and location of the service.

The basic functionality for computing, storage, and network combined infrastructures is the intelligent provisioning of the applications and services and adapting the infrastructure to meet the requirements in terms of performance and functionality. Key performance indicators are the number of service instances, the performance per service instance, and the reaction time of services. To achieve premium quality of experience, the resources need to be available and guaranteed for all the resources in the infrastructure. The rich service functionality needs the infrastructure to be able to meet a variety of requirements along multiple dimensions.

1.2.4 The green challenge

Green technologies and carbon emission reduction are key to reduce the ecological impact of the communication industry. With rising energy prices and the impact on the global climate, there is a global consensus on further emphasizing green technologies. The energy consumption of the network itself is to be managed and reduced whenever possible.

Beyond the direct consumption of the network, the wide availability of a business grade communication infrastructure will have an important impact on the overall CO2 emissions of a society. Especially since the beginning of 2020, more in person meetings have been replaced by virtual meetings, significantly reducing the carbon emissions due to travel. This can play an important role in numerous scenarios [1]. Some examples and their issues are given below.

1. High quality virtual team meetings still have a way to go. For more effective meetings, virtual presence meetings will be paramount. Also, interaction on advanced virtual white boards that allow for a direct interaction of all participants will be key for even more productive meetings of people working together remotely [2].

2. Virtual presence for international conferences should not only allow for listening to talks presented or browsing posters, but it should allow for a direct interaction of participants independently on where they are.

3. Online sales meetings would have a significant impact, reducing emissions for travel, hotels, and meetings. This would change the impact of a meeting from days to a few hours. Even interactions with machines through a virtual presence system could be made possible.

4. Consulting services could be provided remotely, avoiding significant amounts of air travel.

5. Virtual consultations of medical doctors through advanced medical sensors to allow for an immediate real-time evaluation would play a key role. This would reduce emissions due to reduced travel, and also reduce the risk of spreading diseases. This requires advanced medical technology that can help a doctor assess in-situ the health of a patient, support diagnosis, risk mitigation, and prevention.

For all this, sufficient quality, low latency, reliability, and bandwidth are needed.

[1] https://publications.tno.nl/publication/34638084/98Qn55/niamut-2021-social.pdf

[2] https://www.sustainability-times.com/sustainable-business/virtual-meetings-have-power-to-lower-carbon-emissions

1.2.5 Business Environment Change

The closer cooperation between network and computing capabilities is expected to have an impact on the service provider's business environment and the services offered by digital service providers. The expectation is that computing integrated network combined services will be provided to customers independently of whether the services are more IT, media, or communication oriented. The industry structure of such service offering are open and various options are possible. Whether those combined services are produced on the same or independent infrastructure is open, but the expectation is that a high degree of flexibility in the infrastructure is required to support the various cases being deployed. New interfaces between computing and network are needed and required to be standardized.

In the case of computing integrated network infrastructure, common optimization of computing and network resources and combined management of the service quality can be achieved. The services can be easily guaranteed by doing this. The service provider infrastructure will need to migrate to a platform approach allowing for a plethora of different services being produced on the same infrastructure.

2 Capability Dimensions for F5G Advanced

The scope of the F5G advanced system can be described in terms of six dimensions, as shown in Figure 2. Three of them are direct enhancements of the existing dimensions of the F5G project: eFBB can be made faster, GRE can be made faster, and FFC can be made wider. The others are new directions: greener, smarter, and more aware networking. In addition, trustworthiness of the network is a foundational principle that must not be neglected.

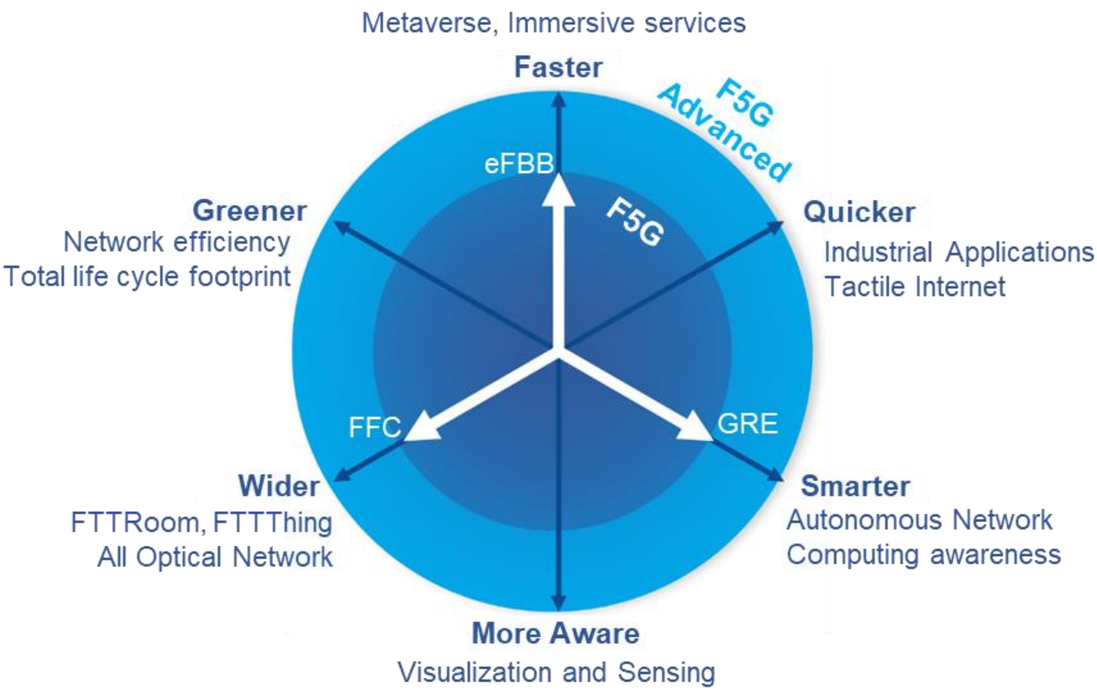

Figure 2: The six dimensions of F5G Advanced

2.1 Faster: Increasing bandwidth

Application bandwidth has been growing at a rate of about 40% per year, and this is expected to continue [3]. The sources of this growth include the increase of the number of endpoints, the proliferation of more and more applications (metaverse and immersive services), and the expansion of usage in existing applications. The fixed network needs to keep up with this growth, and that implies modernization of the transport, access, and home networks.

In the optical transport network, the predominant technologies in the F5G era include 200G and 400G per lambda. Bandwidth growth in the F5G advanced era can be accommodated by increasing this to 800G per lambda coupled with increasing the number of wavelengths / channels. The default optical access system in F5G is XG(S)-PON, and this continues to grow in popularity. 50G-PON is the next system in the pipeline and will begin deployments in the F5G advanced timeframe. For the premises network, there are several means to improve bandwidth, including Fibre-To-The-Room (FTTR) and upgrading from Wi-Fi 6 to Wi-Fi 7. The spectrum aggregation techniques of the latter will enable both more capacity and seamless handoffs.

2.2 Quicker: Reducing latency

The emergence of UHD immersive experience services is a major driver for reducing latency in networks. For tactile internet applications, users need very quick responses. Another important driver is industry applications where the communication is mainly between machines, usually requiring immediate action-reaction times.

Current PON standardized technologies, based on TDMA schemes, do not fully guarantee these conditions of latency and jitter or avoid potential rogue ONT (though with very low probability), creating the demand for new solutions that can ensure the required real-time and reliable connections.

Optical L1 hard pipes, real-time field bus communication, industrial-grade security, and electromagnetic interference immunity capabilities are used to extend optical networks to industrial sites and provide industrial bus optical transmission, meeting strict industrial control requirements. The digital transformation of the energy and transportation industries requires hard pipe connections with high bandwidth and reliability. The optical service unit (OSU) hard pipe technology provides flexible link bandwidth from 2 Mbps to 100 Gbps, low latency of 1 ms, and connections with 99.999% reliability and physical isolation, facilitating digital transformation of industry production networks.

2.3 Wider: Increasing the network scope and number of endpoints

In F5G-Advanced, both the network scope and number of endpoints are expected to be increased to support more services and coverages, as well as the ongoing cloud-network synergy that is built on the underlying network. F5G-Advanced aims to serve as the cornerstone of the network by providing high-capacity, high-performance, and high-reliability ubiquitous intelligent bearer for the cloud and digital transformation. F5G-Advanced will thus focus on the All-Optical Network (AON) that is divided into backbone, metro, access, and data center interconnection (DCI) optical networks, as shown in Figure 3. Different physical layers of networks have different requirements and are supported by different technologies. The service plane is supported by the different layers of the all-optical networks, with further enhancements in backbone and inter-city networks. In addition, F5G-Advanced will provide strong support to data centers (DCs) at all levels.

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[3] https://www.cisco.com/c/en/us/solutions/executive-perspectives/annual-internet-report/index.html

Applications driving this dimension include Fibre-To-The Room (FTTRoom) improving with smart homes, and Fibre-To-The Thing (FTTThing) improving fibre based IoT applications in machine to machine communication.

Compared with F5G, F5G-Advanced will also cover more advanced physical layer technologies, such as 800-Gb/s speed optical transceivers, multi-band optical amplification covering the C, L, and S bands, new optical fibres such as ultra-low loss fibres (e.g., G.654E-compliant fibres), ultra-high-dimensional reconfigurable optical add/drop multiplexers (ROADMs) of up to 128 degrees, and flexible wavelength routing with colorless, directionless, and contention-less ROADMs. With these advances, F5G-Advanced is expected to serve as the cornerstone of the new information and communication infrastructure for the upcoming cloud and digital transformation.

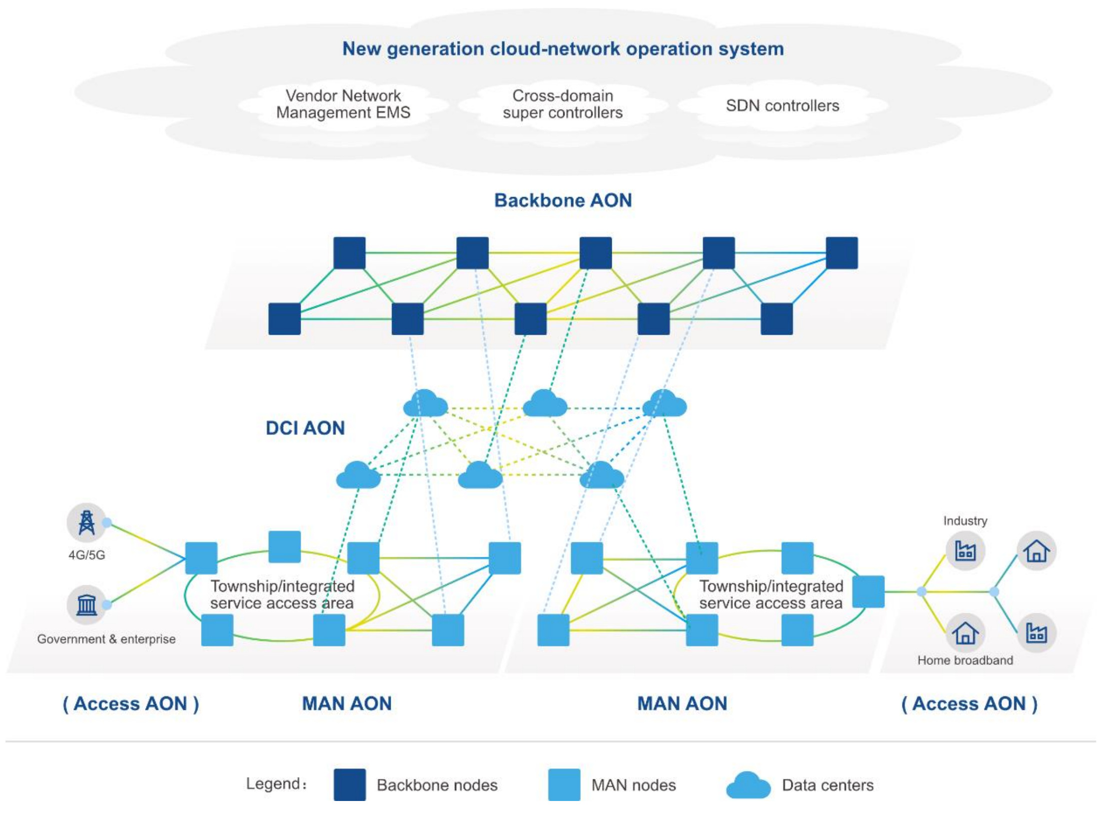

Figure 3: Illustration of F5G-Advanced all-optical access network, including metro, DCI, and backbone networks. AON: all-optical network; MAN: metropolitan area network; DCI: data centre interconnection; EMS: element management system; SDN: software-defined network

2.4 Greener: Enhancing energy efficiency

The transition to green energy is a global challenge. The European Green Deal, approved in 2020, is a set of policy initiatives by the European Commission with the overarching aim of making the European Union (EU) climate neutral in 2050 [4]. To reach climate neutrality, one goal is to decarbonize the energy system and reduce greenhouse gas emissions, by using clean energy from renewable resources and prioritize energy efficiency. More than 75% of greenhouse gas emissions within the EU are related to the production and use of energy.

ICT and specifically F5G advanced can contribute significantly to the above targets. The direct contribution will bring energy efficiency gains through a transition to more efficient F5G advanced optical networks in communication systems and data centers. The indirect contributions are when the F5G network enables novel ways of living, working and meeting (e.g., through augmented / virtual reality applications with excellent user experiences, which reduces the need for user mobility), and improving energy efficiency in other sectors. ICT with F5G advanced with IoT enabled services can also provide the tools for reliably measuring energy consumption of (consumer) electronics, internet and cloud services, or any other energy consuming device or service. These measurements will raise awareness of governments, industries, and citizens about energy consumption and thereby enable consumer choice when it comes to choosing the more efficient service.

The ICT industry will contribute directly by minimizing the energy consumption of the fixed and mobile network infrastructure and data centers, and by creating insight in the energy consumed by the associated computing resources in the network. Optical networks play a vital role, as electrical copper-based networks (both in-home and broadband access networks like xDSL and coaxial-based networks) are phased out in favor of significantly more energy efficient all optical networks [5] integrated with wireless access points and mobile base stations to support mobile and Wi-Fi user equipment.

Within an end-to-end optical network for FTTH, about 2/3 of the energy is consumed by the optical access network (60% ONU, 7% OLT [6]) and 1/3 by the core and aggregation network. To keep power consumption under control, F5G Advanced therefore needs to tackle all aspects of the fixed network, with a special emphasis on reducing power consumption in optical access networks. This can be achieved by developing energy-efficient technologies for optical network elements (ONU, OLT). For example, energy-aware switching and routing or application-specific energy reduction to optimize the distribution of higher definition video streaming can reduce consumption. Power saving modes of optical networks integrated with mobile and wireless access points or locating certain network functions (keep alive) to the optical edge can also help. Another aspect to consider is the reuse of significant parts of the network equipment when upgrading the network. For example, compatibility with ‘plug-in modules’ in network elements can enable upgrades to higher access speeds.

The total life-cycle footprint of networking equipment is another area of concern, where F5G-Advanced provides the mechanisms and migration capability to minimize the overall footprint.

4 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

5 https://www.oecd.org/sti/broadband/broadband-statistics-update.htm

6 https://e3p.jrc.ec.europa.eu/communities/ict-code-conduct-energy-consumption-broadband-communication-equipment

2.5 Smarter: Integrating computing

The integration of computing into the network has several benefits and possible directions. We need to differentiate between the use of computing and the providing of computing. Computing is used in the network for a smarter operation of the computing integrated network. The model to provide computing and storage as a service to customers will allow for additional value-added services.

The other aspect of integrating computing is the way of using artificial intelligence (AI) to make things smarter. This means that AI is used to improve the smartness of operating the computing integrated network and orchestrating the various services provided to customers. In addition, AI in the network can be provided as a service to customers, which poses different challenges to the communication network.

In order to operate computing integrated networks, we need to increase the autonomous levels to level 4, the level of “high autonomy” according to the TM Forum Autonomous Networks paper [[7]]. This allows for self-configuration, self-healing, and self-optimization in network operation. This in turn improves the user experience and service quality in several dimensions including

- Automatic provisioning reducing the fulfillment time
- Reliability guarantees by increased fault handling efficiency
- Smart diagnosis of the network quality, enabling fast fault localization and predictive maintenance
- Optimization of roll-out and capacity through intelligent predictive network planning

Another aspect of computing integrated networks is the capability to increase the service richness. There is much more freedom to create attractive services beyond pure communication. Since the infrastructure can create or operate that plethora of services, smart management of those service is a pre-requisite.

2.6 More Aware: Improving network operations, leveraging new services

Sensing technologies introduce a new dimension to networks by enabling awareness of the surrounding environment. This will leverage enhancements on network operations and will add value to network resources through the development of new services based on this network capability.

Optical networks are today the fundamental backbone for all types of communication. Ubiquitous optical networks will require digitized management and enhanced environment awareness capabilities.

Optical cables, being passive resources, can leverage their optical sensing capabilities to introduce enhancements to their management. Among these are to accurately visualize ODN fibre infrastructure topology and connection status of the Fibre Access Terminal (FAT), to accurately identify real-time optical cable degradation and health prediction, to give advance warning of a possible failure occurrence, and to detect shared-route situations where the same-cable and same-duct are being used for the working and protection route. These requirements are already being tackled in some of the work developed in ETSI ISG F5G group, namely in several use cases as “Intelligent Optical Cable management” and “AI-based PON optical path diagnosis”, complemented with the “Digitalized OND/FTTX”.

[7] https://www.tmforum.org/resources/whitepapers/autonomous-networks-empowering-digital-transformation-for-smart-societies-and-industries/

F5G defined Guaranteed Reliable Experience (GRE) as one of the key F5G dimensions to ensure multiple services with different experience requirements to be carried by same F5G network and enable the transition of bandwidth-oriented SLA to experience-oriented SLA. It is important to enhance the user experience by making the user experience visible and manageable in F5G Advanced networks. The following aspects need to be considered to enable this transition:

1. Definition of the service experience indicators and corresponding categorizations for different scenarios such as home broadband, enterprise, industry manufacture, as well as establishing the relationship functions between service experience and network KPIs
2. Visualization of the user experience in real time via use of probes, collection, and analysis of network KPI using technologies such as telemetry and assess the service type of each network connection and generate service experience quality measurements.
3. Predictive experience optimization: Analyse network KPI with the use of AI, predict potential risks or issues of service experience degradation, and develop solutions to improve the service experience.

Furthermore, the sensing capabilities of the optical network can unleash a new world of non-network related applications. Multiple use cases are enabled by the real time and high precision capture of various environmental parameters such as positioning, vibration, temperature, and stress. Some applications being studied include a) the oil and gas industry, where optical sensing can detect and localize intrusion and sabotage events around the clock and implement unattended inspection to improve pipeline reliability; b) Enhancing digital 3D map generation, and indoor robot navigation in smart factories; c) Early prediction of earthquakes using optical submarine cables.

The wide area of application for sensing technologies, in fixed and wireless optical communications and in Wi-Fi, is a very relevant new dimension for F5G networks evolution.

2.7 More Trustworthy

Optical network trustworthiness mainly includes two aspects: data security and bearer network security. User data involves sensitive personal data, national data, and enterprise core production data, which impose high requirements on data security. In terms of bearer network security, computing-oriented scheduling needs to collect a large amount of network information and computing-power information. Data centralization increases the need for the protection of sensitive information. Computing-capability awareness and transport also increase the need for network trustworthy in cross-system, cross-domain, or cross-border network connections.

3 Key technologies for F5G Advanced

To meet future development requirements such as user quality improvement, digital transformation of production networks, and experience operation transformation, the target F5G advanced network requires seven network capability features to enable F5G to evolve into the future. These are explained in the following sub-sections and summarized in Figure 4.

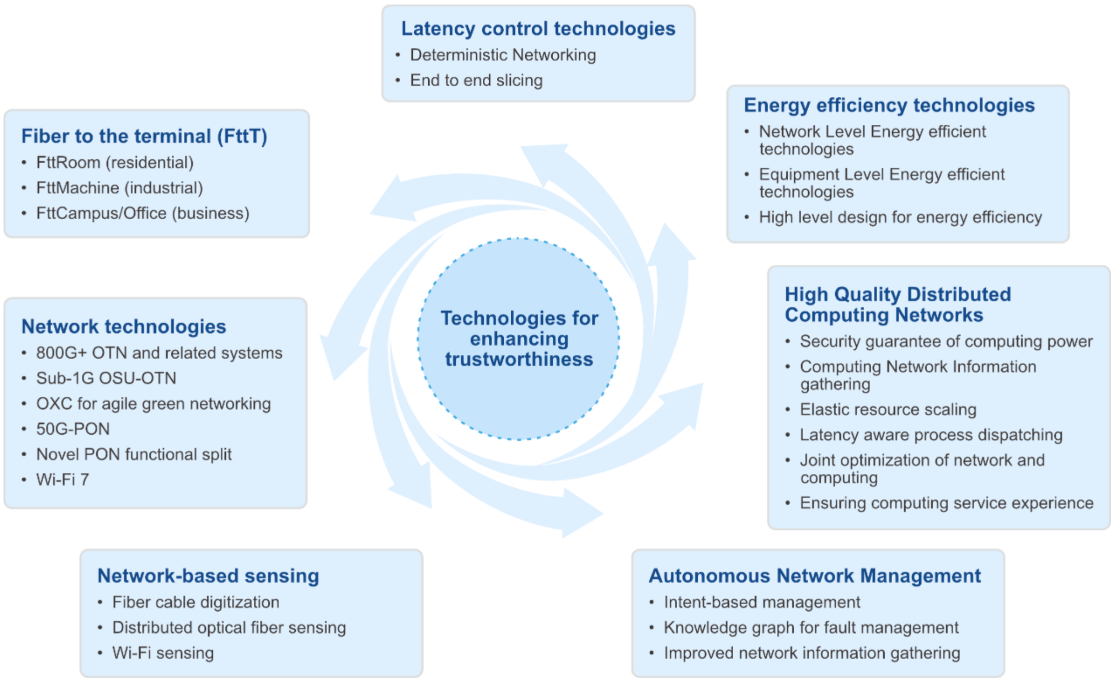

Figure 4: The key technologies of F5G Advanced

3.1 Network technologies

In the F5G architecture, there are three major divisions of networks: transport, access, and home. The following technologies are identified as important to support the evolution of F5G advanced networks.

3.1.1 800G+ OTN and related systems

In the Optical Transport Network (OTN), the major standardization bodies are the ITU-T SG15, the IEEE 802.3 working group, and the Optical Interworking Forum (OIF). While these bodies produce distinct standards, the underlying technology is quite similar. Also, much work has gone into making the different standards relate to each other in an interoperable way. The following discussion is meant to apply to all of them.

The existing 200G and 400G transmission technologies are relatively straightforward improvements on the basic 100G coherent technology. Essentially, baud rates and modulation constellations were increased. To go further, beyond-400G (B400G) technologies include 800G+ transmission, additional flexibility in the modulation rate and format, as well as other features such as constellation shaping and advanced error correction. This allows the B400G systems to achieve the best data rate for any optical channel condition.

3.1.2 Sub-1G OSU-OTN

In F5G-Advanced, the OTN is enhanced to provide not only the B400G capability, but also the sub-1G capability that allows the OTN to directly support a much larger number of services (e.g., ≥4000 services per 100G) than the traditional OTN that carries up to 80 services per 100G. The sub-1G capability is enabled by the use of the Optical Service Unit (OSU), which is being standardized by the ITU-T under the G.osu work item. To ensure the stability of the optical service network architecture, all-optical anchor points can be established to promote integrated service access and one-hop access to the cloud.

The all-optical anchor points are the connection points between the optical network and services, which can steadily promote integrated service access and improve resource utilization. Various access technologies, such as PON, G.metro, OSU, and OTN, can be used to implement efficient and flexible bearing of services at different rates from a few Mbit/s to over 100 Gbit/s. In addition, with the service awareness capability of optical networks being continuously enhanced, optical networks are reaching closer to the end users to provide ubiquitous optical connection services, ensuring that the end users can easily obtain and use both the networking and cloud computing resources.

3.1.3 OXC for green, agile and flexible optical networking

To achieve low energy consumption and low transport latency, it is desirable to use optical cross-connects (OXCs) in an end-to-end large-capacity all-optical network covering backbone and metro networks wherever appropriate. For backbone and metro-core networks, high-dimensional OXC with a degree of up to 128 needs to be designed and developed. For metro-edge networks, F5G-Advanced aims to expand the footprint of WDM technology to build smart cities and smart villages more economically. For this, cost-effective low-dimensional OXC with 4 to 9 degrees can be used to replace the traditional fixed optical add/drop multiplexers and achieve reconfigurable optical add/drop multiplexing. This feature enables flexible and dynamic metro networking.

3.1.4 50G-PON

50G-PON technology is widely seen as the next step of optical access evolution. The system is defined in the ITU-T G.9804 series, where the first version describes a single channel system with 50 Gb/s downstream and 12.5 Gb/s or 25 Gb/s upstream capacity. Future enhancements will include symmetrical 50 Gb/s operation and multi-channel operation. The primary technical advancement in 50G-PON is the use of DSP to resolve many of the PON and component impairments.

50G-PON has enough capacity that it becomes a viable alternative to a conventional switch-based network. This has potential advantages in that the PON system is centrally scheduled, and completely deterministic in how and when each ONU transmits.

3.1.5 Novel PON functional split

PON technologies exploit specific protocols to transport the data over the ODNs. In the case of ITU-T PONs for example, the TC layer (transmission convergence) is the responsible layer. When data such as an Ethernet frame reaches the top layer of ITU-T PON (SDU layer), it goes through several processes: the frame is fragmented into (X)GEM frames, encrypted, aggregated as GTC frames including the OAM messages, encapsulated with the help of the proper Forward Error Correction coding, and scrambled. Then the resulting signal is transmitted over the physical layer. Once received, the reverse sequence of processing is done.

When two PON systems are simply connected in tandem, a great deal of back-to-back processing will occur at the interconnection point. This redundant processing happens at the user, signaling, and management planes. This represents waste of computational effort and is something to be reduced. One way to do this is by changing the point of interconnection in the TC-layer stack. Alternatively, data for the subtending PON can be encapsulated inside the higher-level PON. Doing either essentially centralizes the higher layer functions and can greatly simplify the interconnecting ONU device. The optimal position of the protocol stack split is to be discussed as several options exist. Also, the concept presented can similarly be adapted to other PON standards as the IEEE PON family, which employs another protocol stack than TC-layer.

A more detailed look at this concept can be found in Annex A.

3.1.6 Wi-Fi 7

Wi-Fi 7 (IEEE 802.11be) is the next system after Wi-Fi 6 (802.11ax). Wi-Fi 7 can achieve 30 Gb/s peak throughput as compared with 9.6 Gb/s for its predecessor. Wi-Fi 7 also supports backward compatibility with all of the previous generations of Wi-Fi and can use the 6 GHz band for higher throughput and lower interference. It supports more MIMO streams. It also promises to have lower latency and support for time sensitive networking, and it supports multi-link operation that enables the simultaneous use of multiple RF bands. Another relevant standard is Wi-Fi 6e, which is basically Wi-Fi 6 using the 6 GHz spectrum. Additionally, spectrum is an issue in some jurisdictions, and the 6 GHz band might not be available. In such cases, mm wave spectrum might be needed.

3.2 Fibre to the terminal

Fibre optics can extend into the home, and into campuses and factories. To fit all these scenarios, we need to continuously enhance the ease of deployment, environmental adaptability, high networking reliability, and accelerate the copper to optical transformation of many industries.

3.2.1 FTTRoom

FTTR integrates home/enterprise networking (intelligent connection of smart devices throughout the house) and edge computing (such as home storage) to implement house-wide connection, control, content, and edge computing capability. This builds an all-optical foundation for smart homes and small and micro enterprises. FTTR optical and Wi-Fi convergence, multi-user intelligent scheduling, and anti-interference algorithms will be further enhanced to provide ms-level service latency, seamless roaming experience, 5 to 10 Gbit/s coverage, and more than 512 concurrent connections. In addition, low-power Wi-Fi is used to connect smart home devices, and optical fibres are directly connected to large smart screens to provide integrated coverage.

3.2.2 FTTMachine

Fibre has the advantages of large bandwidth, long distance, and anti-electromagnetic interference. It is suitable for industrial applications. FTTM maximizes the advantages of optical fibres. FTTM needs to support high network reliability and introduce industrial explosion-proof, dust-proof, shock-proof, and anti-corrosion capabilities. Ring network protection and zero-interruption protection for hitless service switching is to be supported. Efficient symmetric encryption data transmission algorithms and technologies can ensure 24/7 normal operation of production services and achieving nine 9’s reliability. FTTM needs to support the deterministic delay/jitter technology to ensure that the network is controllable. Technologies such as high-capacity/long-distance optical-electrical hybrid cables will be needed for applications without onsite power supply. Alternative approaches such as power over fibre and plastic optical fibres can also be considered. Fast fibre termination technology can achieve quick fibre deployment and flexible expansion within minutes. The miniaturized and ultra-low power consumption technologies of optical and electrical components need to be researched to support the smaller size of remote ONUs, their easier installation, and simplified power supply. To this end, analog radio over fibre techniques might play a role.

3.2.3 FTTCampus/Office

Data center and wireless campus networks have been evolving to use Wi-Fi 6/7. Services such as wireless projection, cloud desktop, and ultra-high definition (UHD) conferencing are to be supported. The 100-meter network cable in the legacy office network cannot support the required bandwidth. Network architecture innovation is urgently needed to implement one-to-one optical fibre connections for campus/office fibre-to-desktop networks. FTTO/D optical fibre to offices and desktops must support 50G PON symmetric high-bandwidth to implement high-bandwidth Wi-Fi 6/7 AP access. Network hard slicing/hard isolation enables the integration of multiple campus networks and hard isolation between multiple networks.

Currently, the typical office network lacks management features and requires manual intervention to configure, find and fix faults, and monitor status. In future it is important to support intent-based deployment, poor-QoE identification, automatic optimization, fault prediction, and self-healing for autonomic network management in a smart all-optical campus. In this way, fibre-to-desktop brings advantages such as high bandwidth, easy evolution, hard isolation, and easy O&M to help smart all-optical campuses.

3.3 Latency control technologies

The requirements for network bandwidth, latency, and jitter are increased with the quality improvement of XR and optical field services and the digital transformation of the industry. In addition, to maximize network efficiency, a network mus have differentiated bearer capabilities to carry multiple differentiated SLA services.

3.3.1 Deterministic networking

Latency and jitter of Wi-Fi interfaces are key bottlenecks in home/campus office scenarios. Wi-Fi 7 uses OFDMA technology, multi-user resource allocation, and multi-link coordination algorithms to implement RU slicing over the air interface. This effectively reduces conflicts over the Wi-Fi air interface, improving service forwarding delay and jitter, and achieving a deterministic low latency of milliseconds to meet service requirements such as XR Pro.

The optical access network can introduce the dual-plane forwarding architecture that adds the TDM forwarding plane to the existing packet forwarding plane-. The traffic that is handled by the TDM-plane can be easily handed over to an OTN system, reducing latency even further. Jitter compensation mechanisms, single-frame multi-burst technology, independent registration channel technology, and collaborative DBA (Dynamic Bandwidth Allocation) technology are introduced to implement microsecond-level low-latency forwarding and microsecond-level service jitter. This can meet the digital requirements of industries such as industrial remote control and precision manufacturing. It is also necessary to maintain the PON in working order so that latency can be assured; therefore, methods to handle rogue ONU and other disturbances are important.

On an optical transport network, the fibre latency per kilometer is 5 µs. The fibre latency is a major contribution to the end-to-end link delay. Selecting the optimal (shortest) physical path based on the network service direction or traffic ownership can greatly reduce the latency. In network planning, multi-path mesh or mesh structure can be considered. The network architecture supports all-optical grooming and small-granularity electrical grooming capabilities, improving the low-latency grooming capability of the network to meet service requirements.

The next-generation OTN container technology for small-granularity bearer will greatly reduce the latency of a single-node devices by reducing multiplexing layers based on virtual channel technology. Connections that meet deterministic low-latency requirements can be based on hard segregated traffic pipes.

3.3.2 End-to-end slicing

E2E slicing ensures SLA experience over diverse Wi-Fi air interfaces, PON networks, and transport networks. By accurately sensing application SLA requirements, dynamic slice creation and on-demand resource scheduling can be implemented, and SLAs can be visible, manageable, and assured. There can be multiple types of slices, include a strict type that reserves resources unconditionally, and a permissive type that allows the reallocation of resources when not in use by the primary slice user. To achieve accurate and fast provision of E2E slicing, F5G Advanced networks need to be able to flexibly configure and combine infrastructure resources and have the ability to analyze and control E2E slicing (as shown in Figure 5).

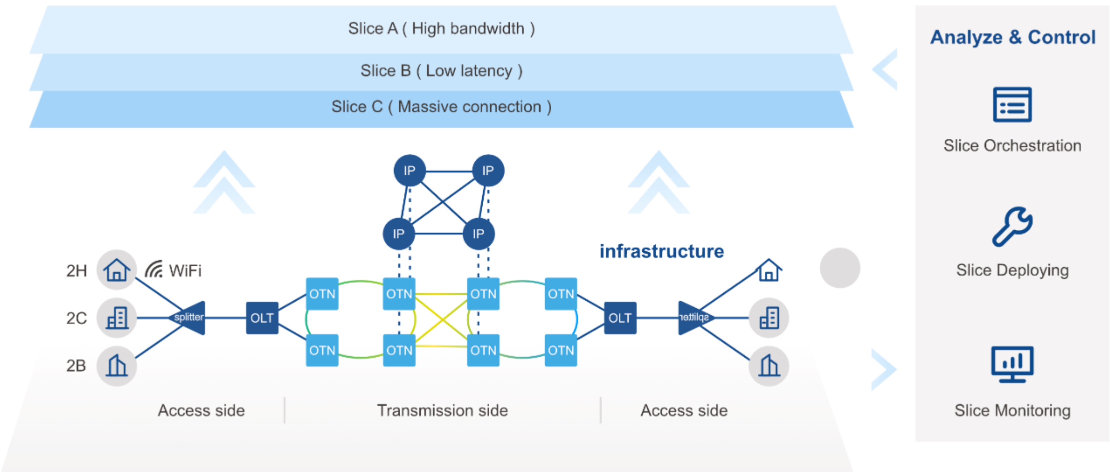

Figure 5: End-to-end slicing

The end-to-end slicing of all-optical network collaboration involves multiple devices in the infrastructure, such as ONUs and OLTs on the access side to OTNs on the transmission side. By properly combining slices of devices in the network, slice creation and on-demand resource scheduling can be implemented. An end-to-end industry private network slice can be formed to implement multiple functions on one network, and thereby provide differentiated bearer services for users in different industries.

The end-to-end slicing of the all-optical network collaboration involves the intelligent management and automatically configuration. For example, based on features of upper-layer services, slice planning will be done for multi-layer network resources. Based on templates of end-to-end slices, the network management system will calculate topology path and deploy services and ensure the isolation of services in different slices. A collaborative management and control system that integrates the full life cycle management of slices is conducive to the flexible deployment of end-to-end network slices.

3.4 Energy efficiency technologies

The energy efficiency of F5G networks can be optimized from three perspectives: network level, equipment level (including dynamic power saving mode) and high-level design.

3.4.1 Network Level Energy efficient technologies

1. Network architecture optimization

The flattened network architecture uses ROADM/OXC (Reconfigurable Optical Add/Drop Multiplexer/Optical Cross Connection) to support optical wavelength bypass. This enables implementing "one-hop transmission of wavelengths". In combination with optical and electrical synergy networking, wavelength grooming and pass-through of intermediate nodes can effectively reduce power consumption of intermediate nodes caused by opto-electrical regeneration.

2. Energy aware switching/routing

In order to efficiently utilise energy, low loaded light-paths can be deactivated, and new light-paths are activated in case of traffic congestion. This can be done based on thresholds specified in the literature and dynamically modify virtual topology of the network.

Light-path (optical) bypass approach and traffic grooming technique can save energy [8]. A transmission path with the lowest power consumption can be selected based on network power consumption, service load and allocation policies.

Algorithms that can take advantage of SDN (Software Defined Networking) to dynamically optimize the network for lower energy consumption. For instance, a proposed algorithm chooses the routes which minimize the number of used network devices [9].

Approaches that take energy into account for operator's other activities. For instance, an approach has been proposed where the location of caching contents inside the network is optimized to save energy [10].

3.4.2 Equipment Level Energy efficient technologies

Power consumption decreases along with technology advancement. For example, by migrating from 200G/400G to 800G per wavelength, the energy consumption per bit will decrease by more than 40%. Similar results in access network can be expected by migrating to 50G PON.

Schemes based on real time monitoring of the network traffic load and resources availability are important. They dynamically adjust network routing, traffic/resource relocation, or power saving modes, when possible, to further reduce energy consumption. F5G Intelligent network management can dynamically force part or all of the network to enter or exit power saving mode based on real time traffic conditions. In the access networks example, power consumption at ONUs can be minimized. Based on the usage and other conditions, ONUs can go into a power-shedding, doze, deep sleep, fast (cyclic) sleep or dynamic power save state. There are various algorithms that can be used to implement power saving effectively.

Co-packaged optics (CPO) is becoming an important direction of green integrated modules. CPO integrates optical interfaces with the logic devices. The rapid growth of traffic in data centres poses challenges to switch power consumption, port density, and capacity. Therefore, CPO has become an important solution. The CPO technology can substantially reduce the space and power consumption required at 51.2 Tb/s switching capacity and above and can be a part of the F5G advanced.

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8 Energy-Aware Algorithms for IP Over WDM Optical Networks | IEEE Journals & Magazine | IEEE Xplore

9 Bringing Energy Aware Routing Closer to Reality With SDN Hybrid Networks

10 (PDF) Energy Efficient Content Distribution in an ISP Network (researchgate.net)

In the case of transport networks, the system can dynamically monitor network traffic and network resources and dynamically control the hibernation of hardware to save energy. On an F5G network, service channels and timeslots can be dynamically adjusted based on the service traffic and bandwidth to reduce the overall power consumption without affecting any services. Key technologies of dynamic energy saving include service/traffic/resource awareness and dynamic energy consumption management. With the development of intelligent networks, dynamic energy efficiency management technologies have become increasingly mature. Dynamic energy saving technologies may substantially reduce energy consumption for typical F5G networks.

3.4.3 High level design for energy efficiency

F5G advanced will have to consider network design approaches that can save energy. The following are some examples of approaches that can be employed.

1. Dynamic placement of power-hungry tasks.

   To minimise energy consumed by power transmission and distribution, intensive tasks that require a higher level of power can be moved dynamically to locations closer to energy sources preferably green energy sources [[11]] or to the locations with low ambient temperatures.

2. Exploitation of residual capacity in the existing light-paths.

   Approaches that take energy into account for operators' activities. For instance, the location of caching contents inside an ISP network takes energy savings into consideration [[12]].

3. Co-existence of different technologies/generations of optical networks.

   Coexistence of generations of equipment allows for graceful as needed upgrades, and this can save overall power consumption.

3.5 High Quality Distributed Computing Networks

Computing networks are by their nature distributed, and they change the usage model from resource-based to task-based. To ensuring high quality, it is necessary to enhance the system capabilities in terms of elasticity, flexibility, and intelligent scheduling to provide network resources on demand. Network resources can be obtained upon use and released when no longer needed.

F5G Advanced uses sub-1G OTN and wavelengths as basic link layer technologies to implement end-to-end dynamic connection setup, flexible bandwidth adjustment, and efficient grooming. To improve the usability and utilization of network computing resources, F5G Advanced uses network computing capabilities such as bandwidth, latency, reliability, packet loss rate, computing power type, and available computing power of nodes as path computation factors. See the network technology aspect above.

In general, a "capacity map" is generated based on the physical resource layer of the computing network to achieve optimal resource scheduling on the entire network. When selecting links for network computation, users can combine path computation factors as required to meet differentiated SLA requirements for quality network computation.

A lot of the technologies currently in use in the cloud platform can be used and enhanced in distributed settings. The digital transformation of banking, government and enterprise is accelerating. Home services are extended to VR, XR, and holographic services. Cloud networks are evolving to computing networks.

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[11] Energy aware routing and aggregation in multilayer optical networks | IEEE Conference Publication | IEEE Xplore

[12] (PDF) Energy Efficient Content Distribution in an ISP Network (researchgate.net)

Cloud computing requirements are increasing. Computing transactions are popularized in the whole society, and computing power is used in a timely manner. However, the combination of networking and cloud needs some more work and development. Therefore, the computing network usage model needs to change from being resource-based to being task-based.

3.5.1 Security guarantee of computing power

In terms of security and reliability, the mode in which data is transferred to remote computing nodes for the calculation will make the service face serious security risks such as network attacks and loss of data privacy. Security needs to be ensured from three aspects: data transmission encryption, data encryption, and risk division of computing nodes (shown in Figure 6).

F5G Advanced focuses on ensuring the security of service data transmission and protecting users' privacy. In the transmission process, encryption signaling, and other methods are used to ensure the security of data before the calculation. The encryption algorithm and the authentication protocol based on physical link attributes can also be introduced to ensure the security of user data and network equipment, which can reduce the maintenance cost of operators.

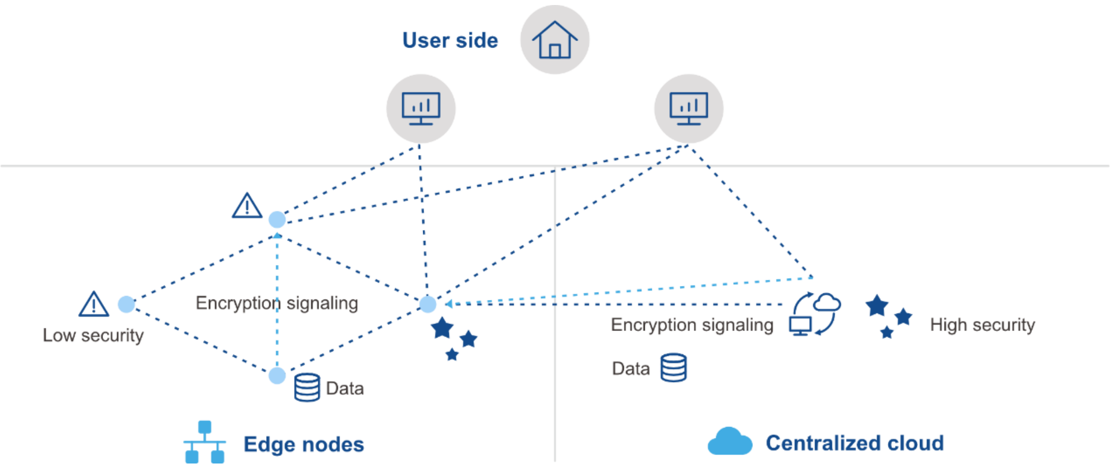

Figure 6: Security guarantee of computing power

3.5.2 Optical Computing & Network Information gathering

The network controller obtains the topology and node information of the user network and computing resource pool across network segments. This enables the computing resource network to automatically establish links between the user network and computing resource nodes. In addition, the network controller delivers the mapping relationship between the type of identification information of the services of different quality and the corresponding bearer link SLA to the physical network edge device.

In this way, the physical network edge device has the capability of automatically identifying the services of different types and correlating the services with the bearer links of different quality. When the service bearer requirement changes, the network controller updates the mapping.

The optical computing awareness capability enables the computing network to detect differentiated bearer requirements of different computing services and do so effectively and cost-effectively. It automatically provides network-level service assurance capabilities and provides basic capability assurance for agile computing scheduling based on computing service requirements.

3.5.3 Elastic resource scaling

One of the most well-known and used function of today's cloud technologies is elastic scaling, which enables the "as a service model". In a centralized cloud, scaling -up, -down, -in, and -out are well-known and implemented. The scaling mechanisms basically take the resource usage and workload placement on resources into account. In a distributed computing scenario, the workload placement and required resource needs must be considered for smart decisions on what workload to place at what location needing a certain number of resources.

Future networks must quickly respond to requirements and have the capability of rapidly establishing connections. The next-generation network will provide fast service provisioning based on paths or wavelengths. It will require minute-level optical-layer wavelength connections and second-level electrical-layer OSU/ODUk connections. The OTN link bandwidth can be adjusted in seconds from 2 Mbit/s to 100 Gbit/s based on changing service requirements.

Connections can be flexibly set up and torn down. Network resources include two types: one is to meet the original static and semi-static connections where resources are planned according to the existing demand prediction mode, and the other is to dynamically schedule and adjust connections on demand. Dynamic scheduling network resources will face the uncertainty of demand, and resources need to be available in advance. Based on the dynamic capability, resources can be reused by multiple service requirements in a time division manner, achieving efficient utilization. Network resources can be planned and monitored online in real time to ensure that resources meet the changing application requirements and ensure suitable redundancy and utilization.

The optical network has the native characteristics of ultra-large capacity, ultra-low latency and jitter that best fit for the high-quality services. In F5G Advanced, the optical network will be further developed on the elasticity and flexibility aspects, and therefore could be used as the bearer network for the distributed computing services.

To enable the task-based mode, the optical network needs to be aware of the network requirements of the computing task (such as destination cloud DC, bandwidth requirements and priority), so that it can provide proper optical connections (such as wavelength/ODUk/OSU connections) on demand, driven by the computing task.

To protect the cloud computing services against network failures, the optical network needs to ensure the high availability (>= 99.999%) of the optical connections, and to provide mechanisms to enable the deterministic recovery time and recovery route.

To support the increasing number of users, DCs and distributed computing applications, the optical network will become larger, and the number of connections per port will be increased by tens of times, to carry massive number of distributed computing services. New control plane technologies will be developed to support the larger scale of optical network.

A proof-of-concept demonstration has been presented in OFC 2022 [13], showing the feasibility of using optical network for real-time cloud-VR services, with the abilities of fine service bandwidth, service-driven optical connection provisioning, and hitless and lossless bandwidth adjustment.

[13] Sheng Liu, Yang Zhao and Yunbo Li, Yongli Zhao and Zhuotong Li, Yi Lin and Jun Zhou, "Optical Service Networks for Cloud VR Application", Show Floor Programs "F5G Update: Emerging Use Cases and Demonstrations", OFC 2022.

3.5.4 Latency-aware Process Dispatching and the Hierarchical Latency Circle

The placement of the processing of a workload is possible in a very flexible way using cloud technologies. For services where end-to-end latency, transaction times, or reaction time on user actions are important, latency is a key performance indicator. For mission critical services, latency might need to be guaranteed.

A meshed network topology is used between different physical computing nodes. Key technologies, such as OXC and protection, are used to build a hierarchical latency circle, for example, for "1 ms-5 ms-20 ms latency"). Computing capabilities can be deployed in metro, regional, and cross-regional pools to meet differentiated computing requirements of different-quality services.

The hierarchical delay circle identifies the physical area that each computing node can cover at each level of delay radius. Therefore, all types of users can efficiently access any computing resource pool distributed on the metro, regional, and cross-regional networks. The SLAs of computing links, such as bandwidth, latency, reliability, packet loss rate, and security hard isolation, can be ensured.

3.5.5 Joint optimization of optical network and cloud computing resources

Cloud computing services are becoming increasingly important, and it is beneficial to jointly optimize the optical network and cloud computing resources [14], as shown in Figure 7. Coordination of network and cloud computing resources on the management and control plane, as well as the forwarding plane, is necessary.

Each network computing resource periodically notifies the network controller of its service capability information, such as a deployment location, a computing power type, a remaining computing power, and a computing power level of the computing node. The network controller can then generate a visualized computing resource map. This can then present multiple computing network links that meet requirements from the user access point to the computing service node. The computing resource map that combines computing nodes and computing networks may be called a computing transport map.

With the flexible workload placement and the improved network latency of optical communication, the service workload can be placed such that latency is low or even low and guaranteed. On the other hand, with the low latency communication capabilities of F5G Advanced, improved multiplexing gains on processing can be achieved by placing more workloads in a more centralized location. Various optimization strategies are possible and allow service providers and users to make trade-offs between resource usage against service quality and user experience. The process dispatching (or workload placement) algorithms need to be multi-dimensional optimization oriented.

[14] China Mobile Computing Force Network Whitepaper, November 2021.

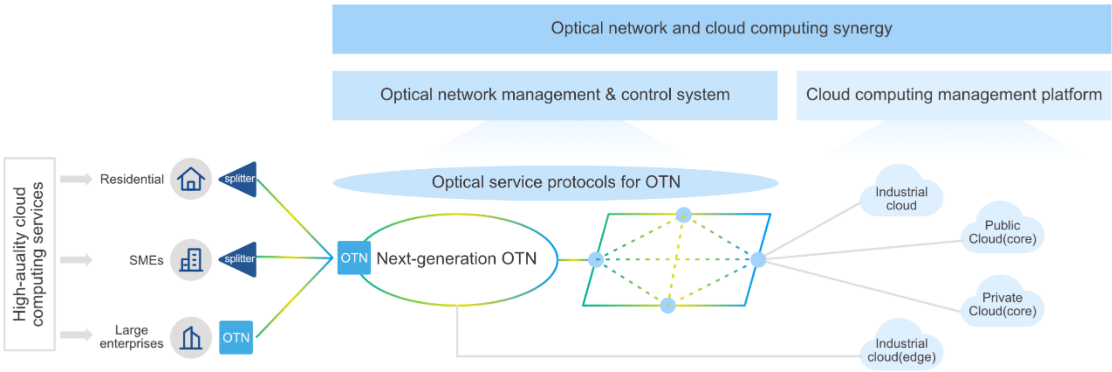

Figure 7: Joint optimization of the optical and cloud computing resources for cloud computing services

3.5.6 High-quality Computing ensuring Premium Service Experience

High-quality computing is a way to have guaranteed computing services over the network, which means the access to the processing resource and the guaranteed computing resource. Basically, the end-to-end network path from customer device to the processing device can be diverse and could possibly include PN, access, aggregation, core, and data-center networks, and is required to be high-quality. All the network elements need to support resource allocation for guaranteed services. The processing device needs to guarantee high quality service guarantees. Computing power can be integrated into the network nodes or can be independent.

For latency-oriented services, the service provider's workload placement system can choose to place workload at the edge of the network in a distance enabling to guaranteed latency and when enough resources are available.

3.6 Autonomous Network Management Technologies

To implement autonomous networking, the Telecommunication Management Forum (TMF) proposes a four-layer three-closed-loop autonomous network (AN) architecture (see Figure 8). Through cooperation and collaboration between the network element layer, network layer, service layer, and business layer, the TMF implements closed-loop management of resources, services, and businesses. It provides consumers and enterprises with a high-quality network that enables zero wait services, zero touch service optimization, and zero trouble network maintenance. It implements network automaticity through core technologies such as service intent-driven, multi-dimensional experience awareness, intelligent bottleneck identification, and network auto-adaptation.

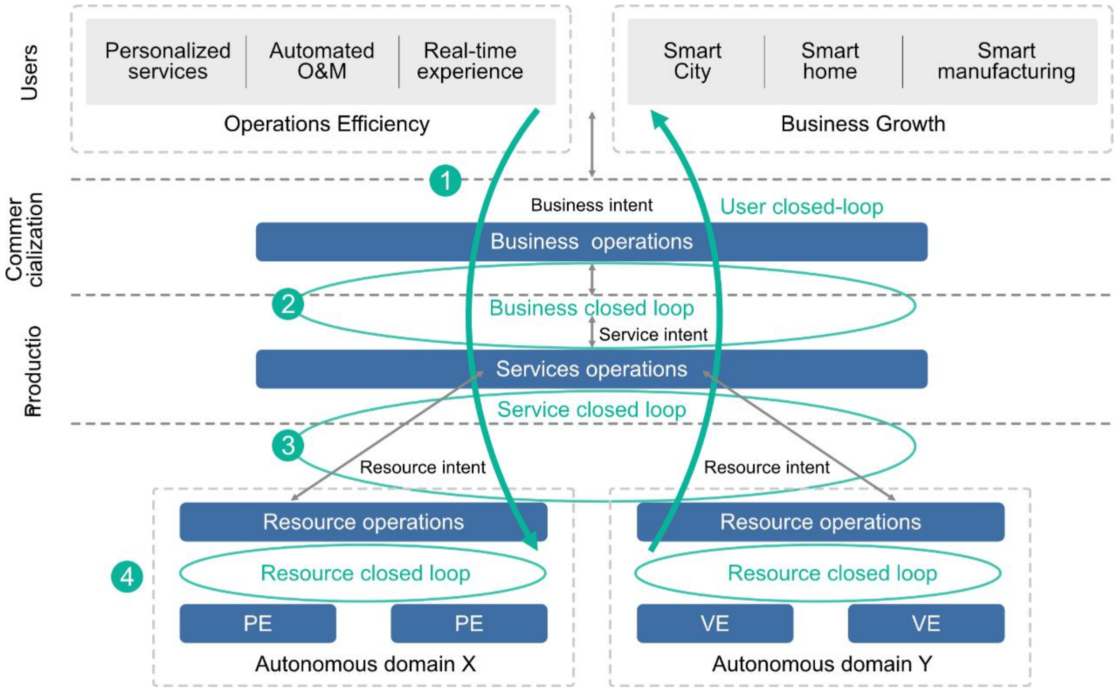

Figure 8: Autonomous network framework (Source: TMF Forum, 2020)

The telecom industry attempted to improve ICT service and network agility, while reducing costs and complexity, through the use of SDN, NFV, and cloud technologies. However, SDN/NFV-based network automation remains unable to completely resolve the problems caused by large-scale deployment of different applications and the introduction of new network technologies. AN, in contrast, attempts to drive the telecom industry from digitization to intelligence by applying multiple intelligent technologies and leveraging the advantages afforded by convergence. This will have a profound impact on methods of production and operation, as well as the skills and thought processes of personnel, across the entire telecom industry.

According to version 3 of the AN white paper, autonomous networks must use intelligence, big data, and cloud computing technologies. Additionally, it defines network autonomy levels (L0 to L5, shown in Figure 9).

Autonomous Levels	L0: Manual Operation & Maintenance	L1: Assisted Operation & Maintenance	L2: Partial Autonomous Networks	L3: Conditional Autonomous Networks	L4: High Autonomous Networks	L3: Full Autonomous Networks
Execution	P	P/S	S	S	S	S
Awareness	P	P/S	P/S	S	S	S
Analysis	P	P	P/S	P/S	S	S
Decision	P	P	P	P/S	S	S
Intent/ Experience	P	P	P	P	P/S	S
Applicability	N/A	Select scenarios				
	P People(manual)	S System(autonomous)				

Figure 9: Six levels of autonomous networks (Source: TMF Forum, 2020)

According to a TMF survey result, 88% of carriers plan to deploy ANs on a large scale within the next 10 years. In addition, some leading operators are actively exploring and practicing ANs based on their service strategy requirements. F5G Advanced will apply those concepts to the optical communication domain.

3.6.1 Intent-based management

The intent is defined as "a set of operational objectives that the network should meet and the results that the network should deliver, defined in a declarative manner, without specifying how they should be achieved or implemented". Intention-driven, essentially reflects the view of humans as external supervisors of autonomous systems. They want the system to meet their needs. The system must meet their expectations and intent is an expression of their needs.

In the self-intelligence network, intention is the natural and efficient way of interaction between humans and machines, and between machines. The intent-based network shields the technical complexity of the underlying network, enables O&M personnel to focus on the value of the network, and simplifies the interaction between service domains, as shown in Figure 10.

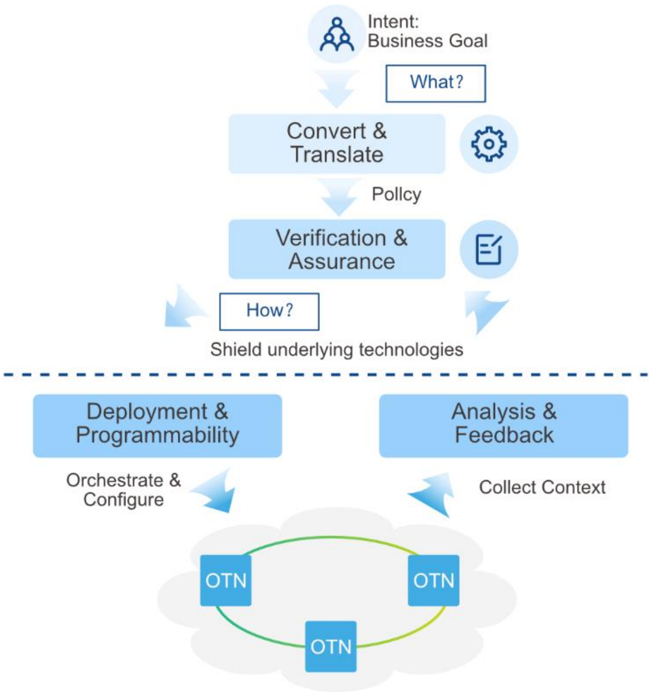

Figure 10: Intent-based management

In carriers' high-value private line service scenarios, intelligent path computation based on multiple path computation factors, such as bandwidth, delay, and availability, helps carriers quickly find the optimal route, achieving 100% automatic provisioning of private line services without manual intervention. The average provisioning period is hours. This feature improves the time to market of private line services.

In scenarios where carriers deploy a large number of home broadband services, real-time service experience analysis, second-level dynamic network status restoration, and multi-dimensional models are important tools. These support precise location of network bottlenecks, implementing adaptive optimization of optical and Wi-Fi networks, and ensuring user-level service experience in real time. This feature ensures zero-fault experience at different levels of home broadband networks, meets people's increasing requirements for broadband services, and helps carriers monetize experience.

3.6.2 Knowledge graph for fault management

Autonomic networking at the network layer includes automatic fault detection, intelligent fault location, fault recovery, and network-level performance optimization. Ideally, it improves O&M capabilities, detects network faults before service interruptions occur, locates the root cause, and rectifies faults before users even notice them. For example, hundreds of alarms are generated when a fibre fault occurs. In the worst case, multiple work orders will be dispatched and maintenance costs will be high. In the AN L4 phase, intelligent inference is performed based on data such as time, space, and user history. The root cause is determined, and a single appropriate work order is automatically dispatched, greatly improving O&M efficiency.

Knowledge graph technology can be used to build an online O&M expert system with knowledge and inference. Interconnected with machine data, the online O&M expert system can process fault data collected and reported by the NMS to automatically identify faults and locate root causes.

It can intelligently respond to queries from network O&M personnel through man-machine interaction interfaces and provide accurate auxiliary fault information. The detailed information, such as the model of the faulty device and troubleshooting procedure, is displayed in a visualized graph. In this way, network O&M personnel can control the fault completely and handle the fault automatically.

In the process of automatic fault root cause inference, rule-based expert system is the most commonly used and effective method. The difficulty lies in that the representation form of inference rules must reflect the fault relationship and network mechanism available. In addition, due to the heterogeneity of different network compositions or domains, various types of unique fault-related information need to be included as much as possible. Once the knowledge graph is established, it can cooperate with a variety of relational inference technologies such as graph-based artificial intelligence to further mine inference rules to update itself, as well as realize automatic fault identification and root cause location according to the inference rules [15]. Figure 11 below illustrates the knowledge graph for fault management.

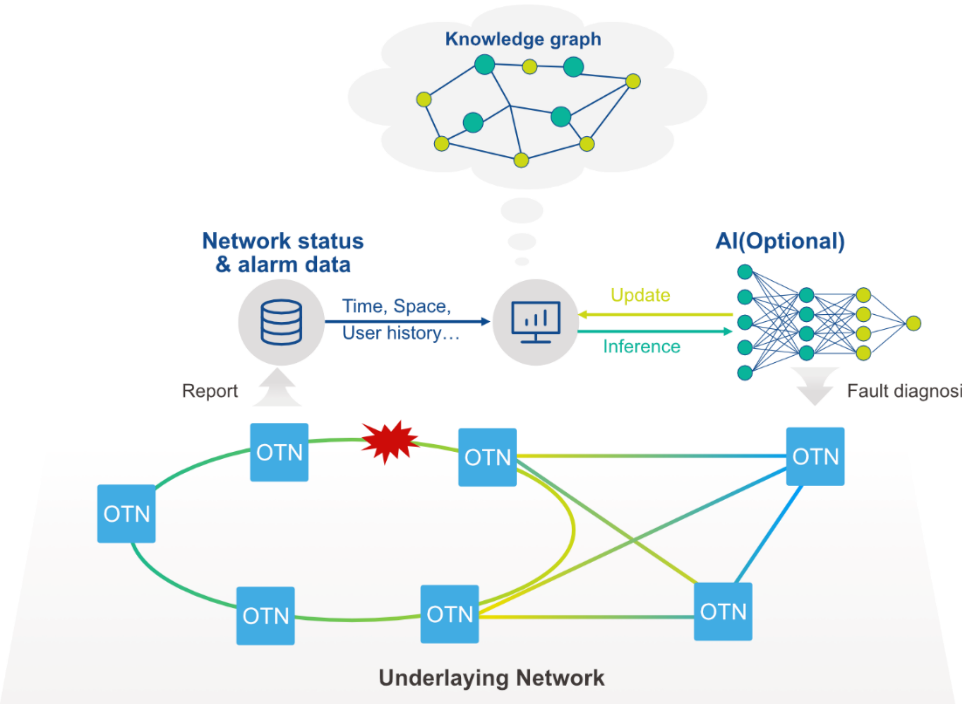

Figure 11: Knowledge graph for fault management

3.6.3 Improved network information gathering

Autonomic networking requires the digitization of optical-layer networks, including the conversion of analogue signals of the original optical system into definite and visible digital signals. It involves the establishment of a sensor system at four layers: optical link layer, optical channel, optical component, and optical service. The goal is to establish a comprehensive, precise, and real-time mass data collection system.

[15] Fault Localization based on Knowledge Graph in Software-Defined Optical Networks | Journal of Lightwave Technology | IEEE Xplore.

On this basis, the resource of optical autonomous network is obtained. Based on the data, the NE layer integrates intelligent prediction and awareness algorithms to further build autonomous capabilities such as proactive fault prediction, automatic recovery, self-optimization of transmission performance, and automatic power consumption control.

Optical systems are complex analogue systems. They cannot be accurately visualized and modelled, which brings difficulties to network performance monitoring, network capacity improvement, and fault locating and recovery. Therefore, optical-layer digitization is a key enabling technology for optical network autonomous driving.

The core of optical communication network digitization is sensors. With digital signal processing, various optical impairments introduced by links can be detected, calculated and even compensated. One typical example of an optical sensor is an Optical Time Domain Reflectometer (OTDR). Using OTDRs, network management systems can obtain information of connection quality of the fibre, such as insertion loss and aging status. Another example is an optical channel monitor (OCM) which can detect optical power and centre frequencies of signals of each wavelength for channel planning or power balancing in a WDM system.

3.7 Network-based sensing

In the F5G evolution phase, multi-modal sensing technologies such as optical and Wi-Fi are used to collect environmental data. When combined with digital twin technologies, they can implement the joint scheduling of communication and perception resources. New convergent awareness service capabilities for networks and industries are then possible.

3.7.1 Fibre cable digitization

By using multiple optical signal detection technologies based on advanced passive photonics and integrated photoelectric detection devices, combining spectral signal event recognition algorithm and computational vision image recognition algorithm, the problem of fibre and passive cable resource management is effectively solved.

It is necessary to add unique tags to the fibres in the ODN segments and branches to aid in their identification. The ODN management system then reads these tags to identify each branch and segment, to enable the reconstruction and visualization of the ODN topology and connecting status of the FAT. AI tools are also useful to help identifying fibre faults/degradations and shared routes.

3.7.2 Distributed optical fibre sensing

Mainstream optical fibre sensing technologies include distributed optical fibre vibration monitoring based on Rayleigh scattering effect, distributed optical fibre temperature measurement based on Raman scattering effect, and distributed temperature and strain monitoring based on Brillouin effect. The technology is characterized by anti-electromagnetic interference, anti-corrosion, easy integration, inherent safety, long distance, and high precision, and has been widely demonstrated in large-scale engineering projects. In recent years, narrow linewidth light sources has been gradually cost reduced and miniaturized. Channel algorithms have been optimized, and artificial intelligence has been applied to process big data generated by optical fibre sensors to implement automatic event identification.

3.7.3 Wi-Fi sensing

Indoor network deployment based on Wi-Fi allows a high throughput data rate with multiple users. Such network can serve to provide Wi-Fi sensing of targets particularly humans, but extendable to objects, animals, and environment. Currently, Wi-Fi sensing at sub-6 GHz is mainly based on measuring channel state information (CSI) which leads to low accuracy due to high wave diffractions and wide antenna beams. Because the indoor environment is complex and susceptible to interference, and the wireless signal transmission is highly dynamic, the wireless signal is not stable, which limits the accuracy of Wi-Fi sensor identification.

Based on the characteristics of Wi-Fi signal propagation, future Wi-Fi perception can be further explored from the following aspects:

Meter-level perception accuracy and resolution improvement: 1) Design signal waveforms and sequences that match refined human body features so that signals can reflect subtle changes in human body features. 2) The multi-MIMO antenna technology obtains more multidimensional radio channel information.

Accuracy improvement beyond 95%: 1) Environment-based anti-interference technology prevents statistical features from being overwhelmed by interference. 2) In awareness mode, the synchronization and coordination technology between multiple APs obtains awareness information of the entire network, making the obtained signal information more accurate and richer.

Moreover, new spectrum such as the mmW enables a new opportunity of Wi-Fi sensing in future to offer a finer accuracy, based on higher available bandwidth, and beamformed antennas with high spatial resolutions.

With this regard, the IEEE 802.11bf Wi-Fi sensing standard enables wireless devices to function as Wi-Fi sensors in license-exempt frequency bands. It covers between 1 GHz and 7.125 GHz and also mmW above 45 GHz. The devices can then act as part of the network to synthesis received signals and determine the location of objects and humans inside their region.

3.8 Technologies for enhancing trustworthiness

The trustworthiness of optical network can be improved at the management and control layer, transport layer, and optical fibre infrastructure layer in F5G Advanced. At the management and control layer, centralized SDN management and control architecture has higher requirements on security of the management and control system, and system-level security assurance measures are required. In addition, DCN network should be isolated from the Internet. O&M tools should be used to reduce external attack risks. IP network security mechanism should be introduced to protect the DCN network. At optical transport layer, network slicing technologies are used to isolate important industry customers, enterprise production services, and common users. Layer 1, Layer 2, and Layer 3 pipe encryption technologies may also be adopted to encrypt network data and improve the security of the bearer network. At optical fibre infrastructure layer, distributed fibre sensing and AI technology can also be used to accurately monitor the operating status of the fibre infrastructure and provide early alarms of any abnormality, and hence improves network security.

4 Beyond F5G Advanced

After the F5G advanced timeframe, there are other technologies that could be considered for the fixed network. The following subclauses describe each of these.

4.1 Optical access network evolution beyond F5G advanced

The next generation of fixed access optical networks should handle the exponential growth of the traffic demands in a more cost and power efficient way and be compatible with the previous generations. It must also add have flexibility, reconfigurability, security and support for fixed-wireless convergence in an environment where a multitude of small-cells will need to be deployed to emit wireless RF, Terahertz and Optical FSO signals. Accomplishing this task will need much more than employing scaled-up improved versions of currently commercially available equipment that are better performing, while maintaining the same point-to-multi-point network architectures that have proved their usability for access Fibre to the X networks.

4.1.1 TDM/TDMA: Reaching its limits

TDM/TDMA based approaches served for decades the PON-based access networks with their cost-effectiveness. However, the requirement for operation with burst mode transceivers at rates beyond 100Gbps, as well as the need for achieving lower connection latencies, could make such a time-slotted based solution prohibitive for use beyond F5G networks. Therefore, to keep the deployment costs and power consumption as low as possible while fulfilling the evolving requirements of access network applications, the current PON architectures needs to be enhanced with new technologies and multiplexing/multiple-access techniques.

4.1.2 UD-WDM-PONs

The Ultra-Dense WDM-PON, (UD-WDM-PON), solution, paves the way to the “spectrum-slice to-the-user” concept. This option shows similar advantages with TDM/WDM-PON in terms of diversity, scalability, higher capacity per user and coexistence with current standards, while it extends the spectral efficiency due to the ultra-dense WDM scheme. The users are allocated a different spectrum-slice as in conventional RF FDM/FDMA based networks or WDM/WDMA optical networks.

4.1.3 Envisioned gradual shift from direct detection to coherent detection

Depending on the larger reach of the passive optical networks that would be needed for various deployment scenarios alongside with the requirements for increased capacities to the end-users, there is a trade-off between the lower cost of direct-detect (DD) systems and the higher capacities and improved reach that can be achieved with coherent (COH) detection technologies. Figure 12 illustrates the transition area that separates the clear use-cases for either DD or COH. However, as technology advances and user requirements changes, this transitioning area is expected to shift to the left at which point the applicability of coherent technologies in passive optical networks will become a commonplace.

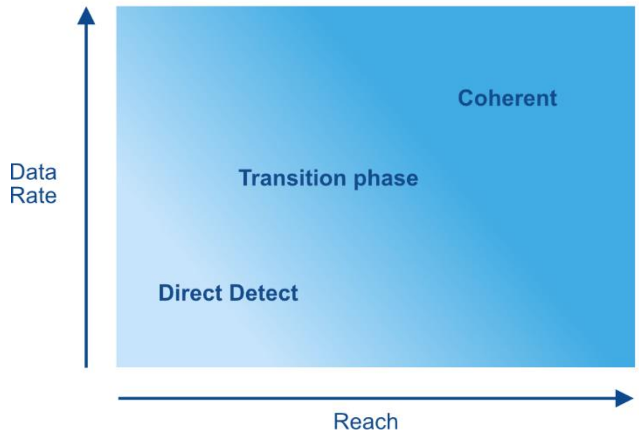

Figure 12: Suitability of coherent versus direct detection systems as a function of reach and rate

Once coherent detection is justified from an end-user requirements and costs point of views, then it opens up the way for radical new changes in the way we design and operate the access networks. One of the first implications would be the possible augmentation or even replacement of TDM/TDMA based traffic handing with approaches that operate on a frequency/wavelength subcarrier domain.

4.2 Wireless-wireline convergence extends to all network segments

As shown in Figure 13, the end-to-end 6G network of the future will span many segments from the RAN to the Core network. The traffic from the RAN sites is directed via the fronthaul to Aggregation Routers that are connected to the Optical Transport network via Optical Nodes (labelled as FLEX-SCALE in the figure). Optical Nodes (ONs) located at the edge part of the 6G network have relatively lower capacity than the ONs that are deeper into the backbone network connecting to Metro and Core Routers. The corresponding optoelectronic interfaces for each of the connections between the 6G cell-cites and the ONs, as well as among the ONs, need to support rates ranging from a few hundreds of Gb/s to ≥1 Tb/s in a single lane (being either spectral or spatial). Some of them can utilized simple DD transceivers, while others need to utilize COH ones. Depending on the 6G segment where the ONs are deployed, their switching speeds is also an important parameter to be engineered according to the corresponding requirements. Switches deep in the Backbone network support the largest throughputs but their switching speeds may be less demanding. ONs that are closer to the network edge need to switch faster to support the low latency requirements, but their capacities will be smaller.

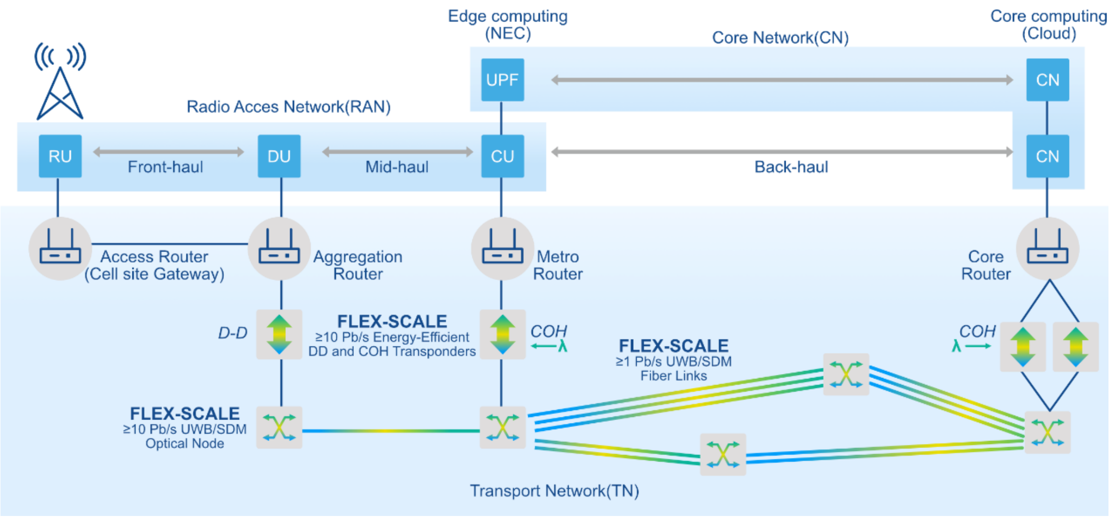

Figure 13: End-to-end converged wireline-wireless 6G network relying on optical fibre communications

The anticipated x-haul 6G optical network innovations will need to achieve record energy efficiency (sub-pJ per switched/transmitted bit) and low cost. This will be enabled by photonic integration and optical transparency, replacing/bypassing power hungry and costly electronic processing systems (e.g., electronic routers/switches). The Optical Nodes (including OLTs at the access network) and their Transceiver Interfaces will be controlled by ML-enabled SDN control plane approaches that incorporate new resource allocation algorithms and protocols. These rely on emerging information models and enabling autonomous programmable disaggregated open networks. These will optimize traffic flow routing across network layers and segments, improving network QoS (high rates, low latency, high reliability/availability) and low cost/power consumption, as required by 6G networks.

Annex A: Novel PON functional split

PON technologies exploit specific protocols to transport the data over the ODNs. In the case of ITU-T PONs for example, the TC layer (transmission convergence) is the responsible layer. When data, for example an Ethernet frame, reach the top layer of ITU-T PON (SDU layer), it consecutively experiences several processes consisting in the TC layer of the following: the frame is fragmented into (X)GEM frames, encrypted, aggregated as GTC frames including the OAM messages, encapsulated with the help of the proper Forward Error Correction coding, and scrambled. Then the resulting signal is transmitted over the physical layer. Once received, the signal is being descrambled, de-encapsulated, disaggregated (from GTC to GEM frames), etc. The processing is coarsely in both directions of transmission. The main difference between upstream and downstream comes from the upstream burst transmission.

When two tiers of PON are cascaded, as proposed by Figure A.1, the data experience several times the TC-layer processing:

- (A): TC-layer processing of ingress Ethernet frame from top sub-layers to bottom sub-layers in OLT1 (Central office (CO))
- to (B): optical transmission from CO to customer premises
- (B): TC-layer processing from bottom sub-layers to top sub-layers in ONU1.A (at customer premises)
- to (C): Ethernet transmission at customer premises from ONU1.A (main ONU) to OLT2
- (C): TC-layer processing from top sub-layers to bottom sub-layers in OLT2 (at customer premises)
- to (D): optical transmission at customer premises, from a room to another for example (from main ONU or OLT2 to edge ONU)
- (D): TC-layer processing from bottom sub-layers to top sub-layers, at customer premises (at edge ONU)

The upstream frames will experience a similar process.

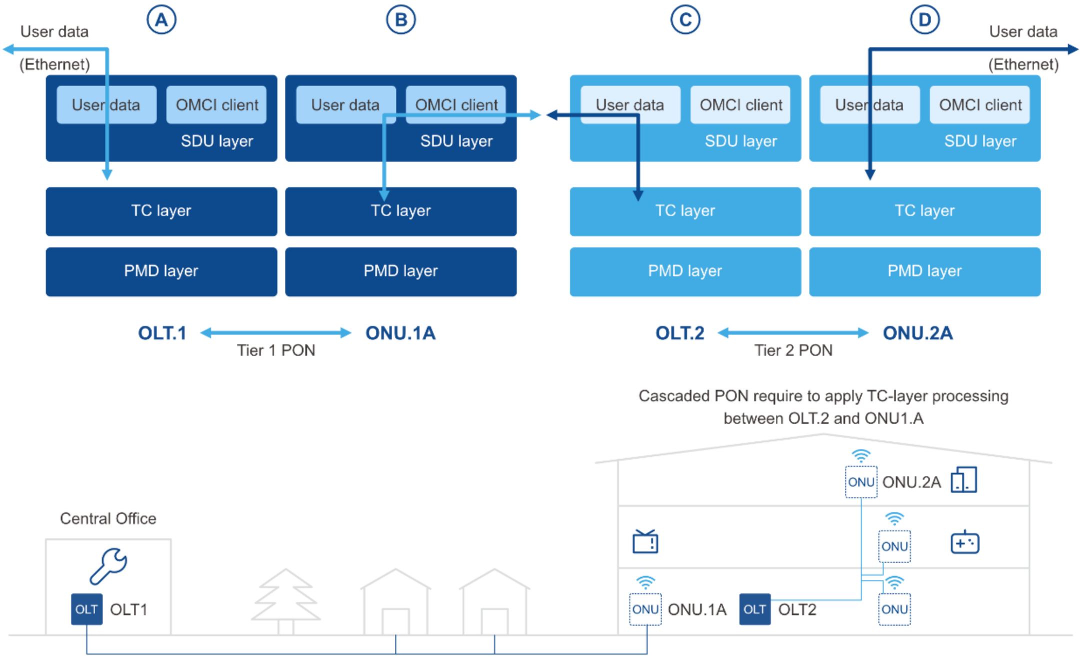

Figure A.1 Cascaded PON with today's technologies

There are ways to simplify these kinds of networks. One method is to partially move the TC layer of OLT2 to the top layers of OLT1 (see Figure A.2). Doing so, we can expect to lighten the processing (calculation resources) required at the ONU1.A and OLT2 (main ONU). The energy required for ONU1A-OLT2 to operate is then also expected to decrease, as the form-factor of the device.

Then, the downstream data reaching OLT1 (at CO) would first be "pre-processed" by the top sub-layers of the second tier PON TC-layer (e.g., Ethernet frame fragmentation), before being "normally" processed by the "regular" TC layer of OLT1 (see Figure A.2). They would then be transmitted from OLT1 to ONU1.A, and the TC-layer processing of ONU1.A would be applied. When reaching OLT2 (customer premises) on Figure A.2, the processing of the lower layers only is to be applied.

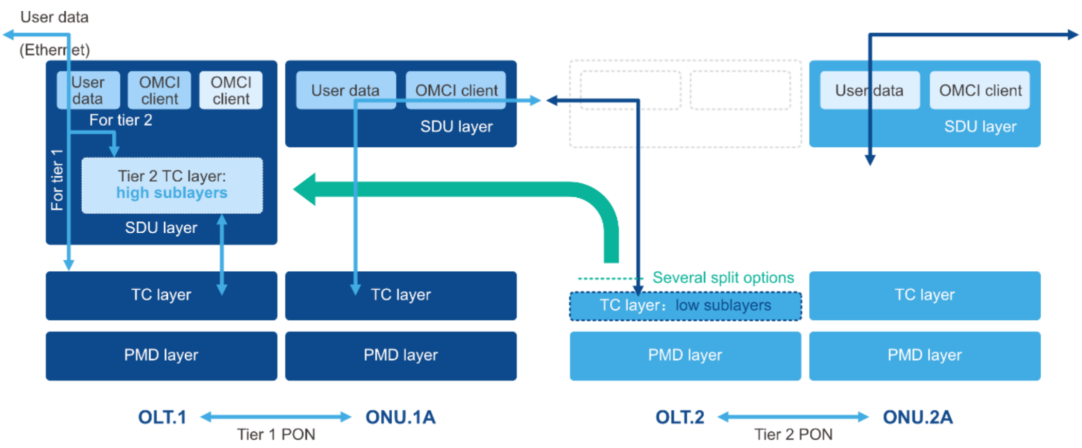

Figure A.2: Proposition: 2nd tier TC layer encapsulation

The optimal position of the protocol stack split is to be discussed as several options exist. Also, the concept presented can similarly be adapted to other PON standards as IEEE PON family, which employs another protocol stack than TC-layer.

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